Wild rice and spadderdock within Tinicum marsh

Sea Level Affecting Marshes Model (SLAMM) Report

Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to John Heinz NWR

Prepared for:

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Contents

Introduction

This is the second application of the SLAMM model to John Heinz NWR. Since December of 2009, a new higher-vertical resolution elevation data set became available as well as additional information about the extent of diked and impounded portions of the study area.

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) suggested that global sea level will increase by approximately 30 cm to 100 cm by 2100 (IPCC 2001). Rahmstorf (2007) suggests that this range may be too conservative and that the feasible range by 2100 is 50 to 140 cm. Rising sea levels may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat "migration" as salt marshes transgress landward and replace tidal freshwater and irregularly flooded marsh (R. A. Park et al. 1991).

In an effort to address the potential effects of sea level rise on United States national wildlife refuges, the U. S. Fish and Wildlife Service contracted the application of the SLAMM model for most coastal refuges. This analysis is designed to assist in the production of comprehensive conservation plans (CCPs) for each refuge along with other long-term management plans.

Model Summary

Changes in tidal marsh area and habitat type in response to sea-level rise were modeled using the Sea Level Affecting Marshes Model (SLAMM 6) that accounts for the dominant processes involved in wetland conversion and shoreline modifications during long-term sea level rise (Park et al. 1989; *www.warrenpinnacle.com/prof/SLAMM*).

Successive versions of the model have been used to estimate the impacts of sea level rise on the coasts of the U.S. (Titus et al. 1991; Lee et al. 1992; Park et al. 1993; Galbraith et al. 2002; National Wildlife Federation & Florida Wildlife Federation 2006; Glick et al. 2007; Craft et al. 2009).

Within SLAMM, there are five primary processes that affect wetland fate under different scenarios of sea-level rise:

- **Inundation:** The rise of water levels and the salt boundary are tracked by reducing elevations of each cell as sea levels rise, thus keeping mean tide level (MTL) constant at zero. The effects on each cell are calculated based on the minimum elevation and slope of that cell.

- **Erosion:** Erosion is triggered based on a threshold of maximum fetch and the proximity of the marsh to estuarine water or open ocean. When these conditions are met, horizontal erosion occurs at a rate based on site- specific data.

- **Overwash:** Barrier islands of under 500 meters width are assumed to undergo overwash during each specified interval for large storms. Beach migration and transport of sediments are calculated.

- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the fresh water table to rising sea level close to the coast.

- **Accretion:** Sea level rise is offset by sedimentation and vertical accretion using average or site-specific values for each wetland category. Accretion rates may be spatially variable within a given model domain or can be specified to respond to feedbacks such as frequency of flooding.

SLAMM Version 6.0 was developed in 2008/2009 and is based on SLAMM 5. SLAMM 6.0 provides backwards compatibility to SLAMM 5, that is, SLAMM 5 results can be replicated in SLAMM 6. However, SLAMM 6 also provides several optional capabilities.

- Accretion Feedback Component: Feedbacks based on wetland elevation, distance to channel, and salinity may be specified. This feedback will be used in USFWS simulations, but only where adequate data exist for parameterization.

- Salinity Model: Multiple time-variable freshwater flows may be specified. Salinity is estimated and mapped at MLLW, MHHW, and MTL. Habitat switching may be specified as a function of salinity. This optional sub-model is not utilized in USFWS simulations.

- Integrated Elevation Analysis: SLAMM will summarize site-specific categorized elevation ranges for wetlands as derived from LiDAR data or other high-resolution data sets. This functionality is used in USFWS simulations to test the SLAMM conceptual model at each site. The causes of any discrepancies are then tracked down and reported on within the model application report.

- Flexible Elevation Ranges for land categories: If site-specific data indicate that wetland elevation ranges are outside of SLAMM defaults, a different range may be specified within the interface. In USFWS simulations, the use of values outside of SLAMM defaults is rarely utilized. If such a change is made, the change and the reason for it are fully documented within the model application reports.

- Many other graphic user interface and memory management improvements are also part of the new version including an updated *Technical Documentation*, and context sensitive help files.

For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 6.0 *Technical Documentation* (Clough et al. 2010). This document is available at *http://warrenpinnacle.com/prof/SLAMM*

All model results are subject to uncertainty due to limitations in input data, incomplete knowledge about factors that control the behavior of the system being modeled, and simplifications of the system (Council for Regulatory Environmental Modeling 2008). Site-specific factors that increase or decrease model uncertainty may be covered in the *Discussion* section of this report.

Sea Level Rise Scenarios

SLAMM 6 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 family of scenarios assumes that the future world includes rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. In particular, the A1B scenario assumes that energy sources will be balanced across all sources. Under the A1B scenario, the IPCC WGI Fourth Assessment Report (IPCC 2007) suggests a likely range of 0.21 to 0.48 meters of sea level rise by 2090-2099 "excluding future rapid dynamical changes in ice flow."   The A1B-mean scenario that was run as a part of this project falls near the middle of this estimated range, predicting 0.39 meters of global sea level rise by 2100. A1B-maximum predicts 0.69 meters of global SLR by 2100.

The latest literature (Chen et al. 2006; Monaghan et al. 2006) indicates that the eustatic rise in sea levels is progressing more rapidly than was previously assumed, perhaps due to the dynamic changes in ice flow omitted within the IPCC report's calculations. A recent paper in the journal *Science* (Rahmstorf 2007) suggests that, taking into account possible model error, a feasible range by 2100 of 50 to 140 cm. This work was recently updated and the ranges were increased to 75 to 190 cm (Vermeer and Rahmstorf 2009). Pfeffer et al. (2008) suggests that 2 meters by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. A recent US inter-governmental report states "Although no ice-sheet model is currently capable of capturing the glacier speedups in Antarctica or Greenland that have been observed over the last decade, including these processes in models will very likely show that IPCC AR4 projected sea level rises for the end of the 21st century are too low." (Clark 2009). A recent paper by Grinsted et al. (2009) states that "sea level 2090-2099 is projected to be 0.9 to 1.3 m for the A1B scenario…" Grinsted also states that there is a "low probability" that SLR will match the lower IPCC estimates.

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 meter, 1½ meters, and 2 meters of eustatic sea-level rise by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure I.1).
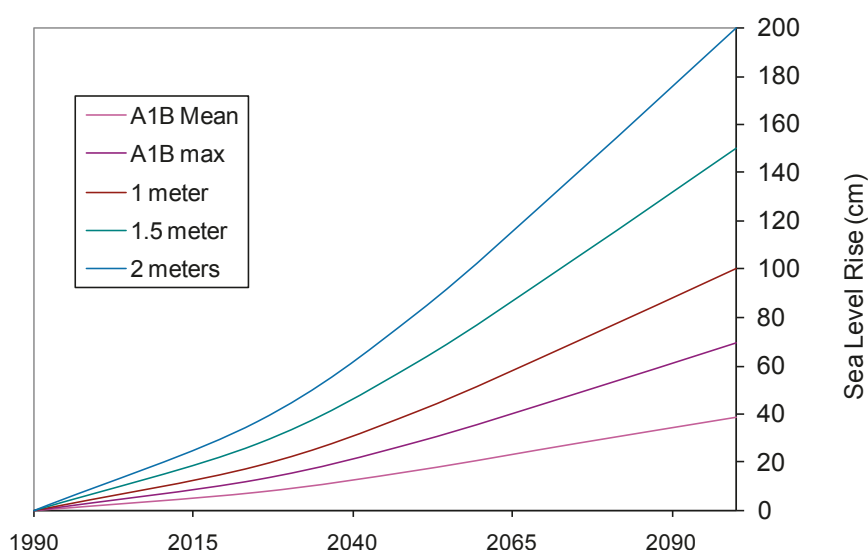

Figure I.1: Summary of SLR scenarios utilized

Methods and Data Sources

The digital elevation map (DEM) used in this model simulation is 2008 LiDAR-derived 2 foot contours originating from the City of Philadelphia Water Department (Figure I.2). A higher vertical resolution LiDAR DEM developed by the Pennsylvania Department of Conservation and Natural Resources for the PAMAP project was not available at the time of writing.

Figure I.2: Contours at 0 feet (green) through 6 feet (red) over DEM of John Heinz NWR.
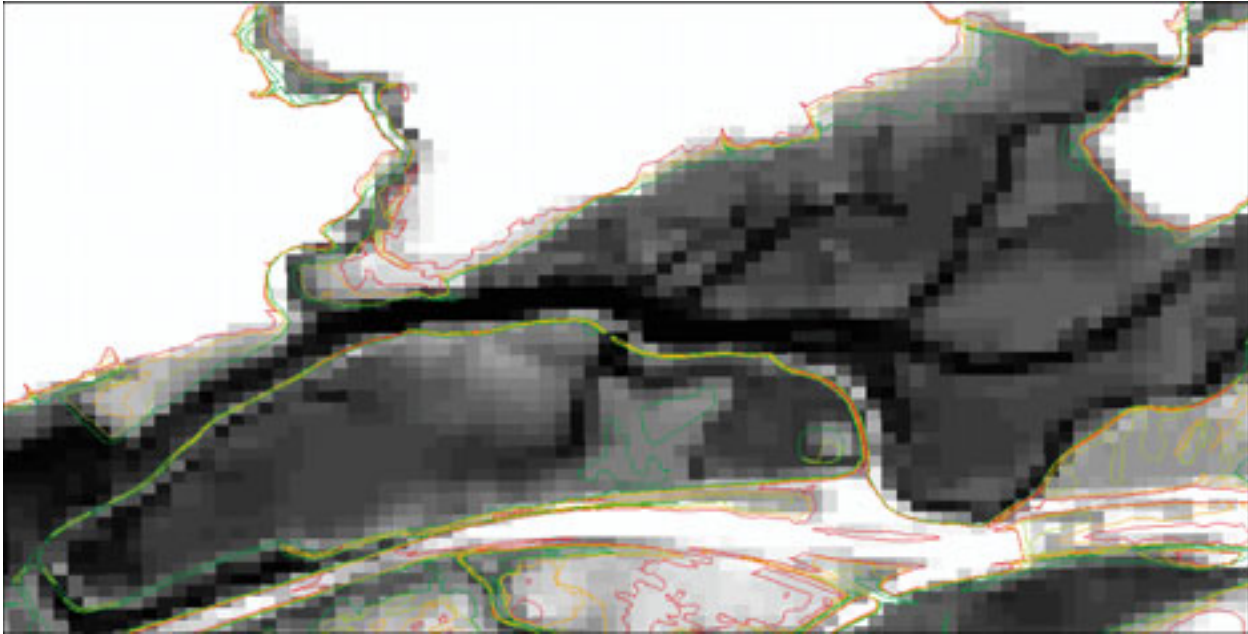
The National Wetlands Inventory (NWI) for John Heinz is based on photo dates of 1989. Several changes were made to the wetland layer based on communication with Brendalee Phillips and Larry Woodward, both from the John Heinz NWR, and Dan Salas, an ecologist from JFNew. Inland fresh marsh in Corps property and Henderson were both changed to tidal fresh marsh based on this communication (Figure I.3).

Converting the NWI survey into 30-meter cells indicates that the approximately 1,200- acre refuge (approved acquisition boundary including water) is composed of the categories as shown below:

	Tidal Fresh Marsh	35.2%
	Undeveloped Dry Land	22.4%
	Inland Open Water	15.5%
	Riverine Tidal	12.1%
	Inland Fresh Marsh	5.6%
	Tidal Swamp	5.2%
	Developed Dry Land	3.5%

There is only one impounded area within John Heinz NWR, that being the freshwater pond at the east of the refuge. Since the previous run, the above-mentioned communication led to the removal of diked status for Henderson and Corps property (Figure I.3).

Figure I.3: Current impoundments (yellow outline) and removed impoundments (black) at Henderson (1) and Corps property (2).
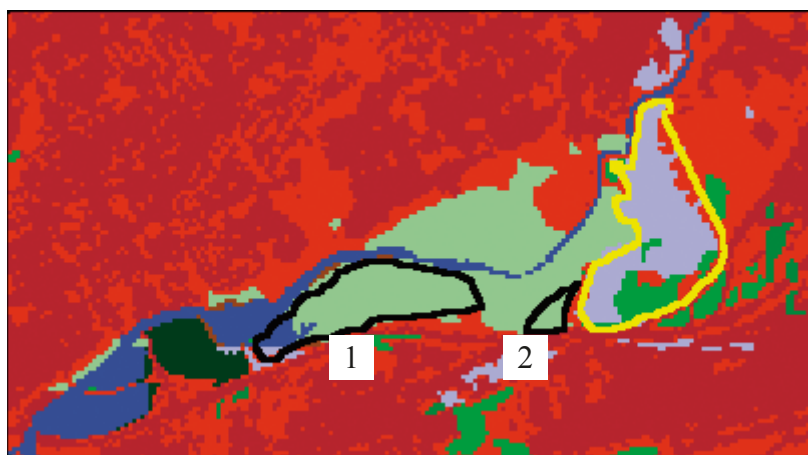
The historic trend for sea level rise was estimated 2.79 mm/year using the nearest NOAA gage (8545240, Philadelphia, PA). The rate of sea level rise for this refuge is somewhat greater than the global average for the last 100 years (approximately 1.7 mm/year).

The tidal range for the John Heinz NWR was specified to vary spatially with two input sites (Figure I.4) using three NOAA tide gages (8542425, Wanamaker Bridge, Darby Creek, PA; 8542699, Norwood, Darby Creek, PA; 8543024, Tinicum 3, Darby Creek, PA) (Figure I.5). Based on these gages, the diurnal range of tide (GT) was estimated at 1.92 meters for the western portion of the refuge and a range of 1.50 meters was utilized in the east.
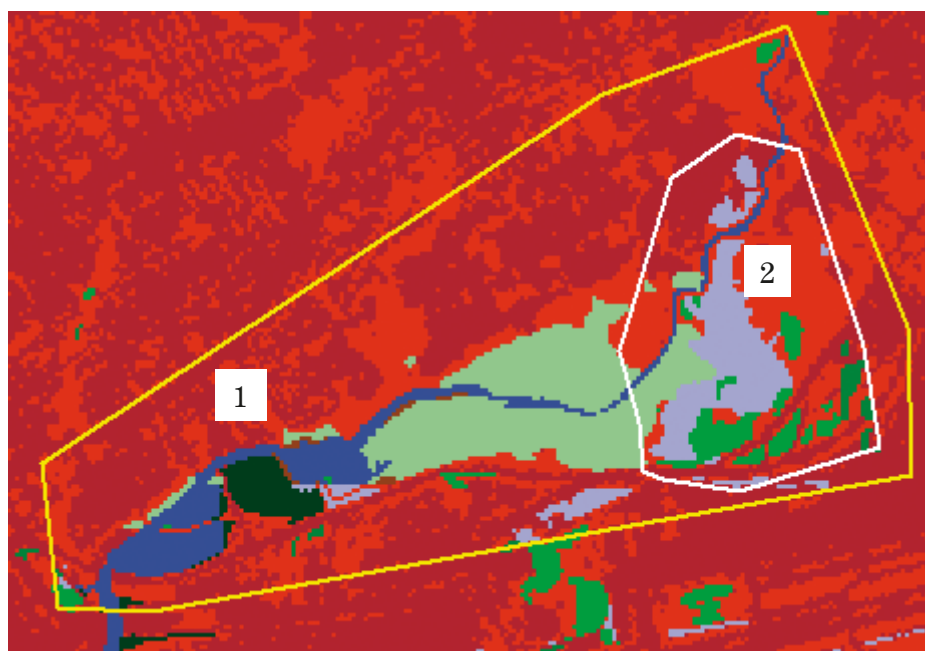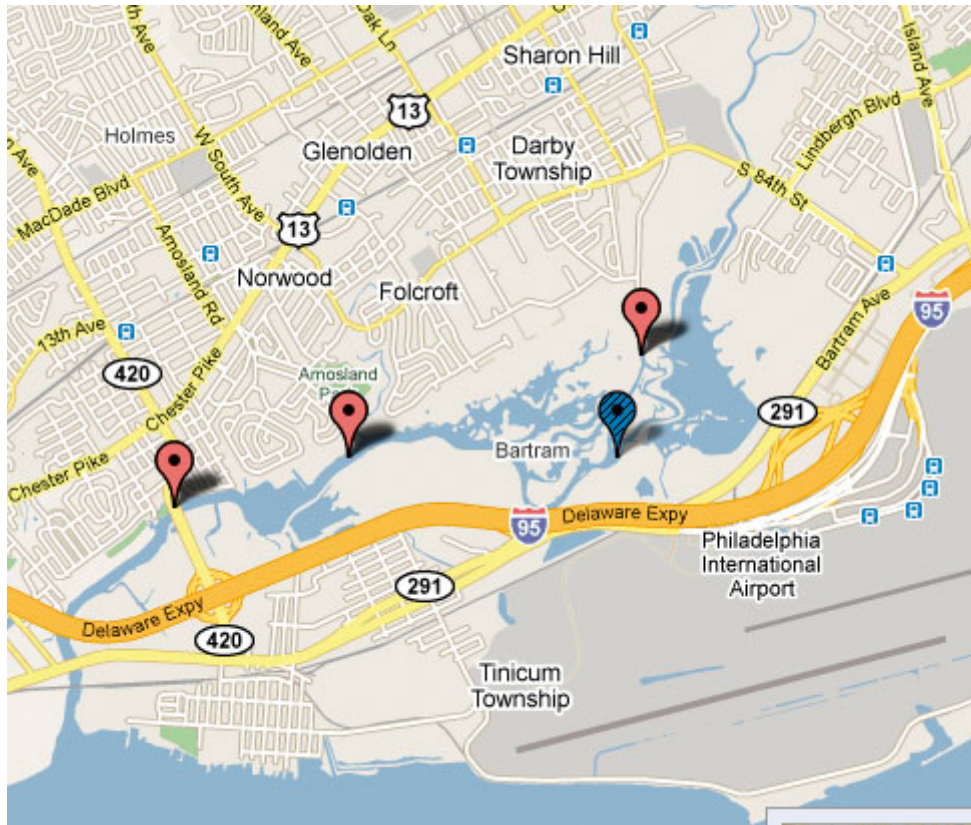

Figure I.4: Input sub-sites.

Figure I.5: NOAA Gage Relevant to the Study Area.

No site-specific marsh accretion data were located for this refuge. The marsh accretion values used were based on a rough average of three different calculations:

- The marsh accretion study located nearest to this study area (Port Mahon DE, Kraft, 1992) measured accretion rates as 4.05 mm/year;

- Based on a large analysis of accretion studies within the mid-Atlantic region (Reed 2008), the average Delaware salt marsh accretion value was calculated at 3.88 mm/yr (n=9);

- Based on data in this same paper (Reed 2008), the average accretion value within Delaware estuaries was calculated at 4.28 mm/yr (n=15)

As these three different calculations are quite similar, accretion rates in regularly flooded marshes were set to 4 mm/year, irregularly flooded marshes to 4 mm/year and tidal fresh were also set to 4 mm/year.

Dan Salas of JFNew indicated that a review of 60-year-old aerial photos indicated that channel erosion was likely lower than 1 foot per year. As a result, marsh erosion was reduced to 1 foot per year (or 0.3048 meters). Swamp and tidal-flat erosion rates for this refuge were set to 2 horizontal meters per year based on long-term measurements of coastal erosion rates in Delaware as presented in Kraft (1992).

Based on site-specific LiDAR-derived elevations, the elevation range for tidal swamp and tidal fresh marsh were altered slightly. Based on an elevation analysis, the minimum elevation for tidal swamp and tidal fresh marsh was set to 0.26 and -0.4 half-tide units respectively. (One half-tide unit is half of the diurnal range of tide or ½ GT.)

The vertical datum used for the available DEM contours is the Philadelphia Vertical Datum (PVD), not NAVD88. Instead of using MTL-NAVD88 for elevation correction values, MTL-PVD was used in this model application. As reported in a paper by Jim Titus, NAVD is 4.63 feet (1.41 meters) lower than PVD (Titus and Strange 2008). The nearest MTL to NAVD correction along the Delaware River was determined to be 0.024 meters, so the MTL-PVD correction used in the model was -1.387 meters (-1.41 + 0.024).

Modeled U.S. Fish and Wildlife Service refuge boundaries for Pennsylvania are based on Approved Acquisition Boundaries as published on the FWS National Wildlife Refuge Data and Metadata web-site. The cell-size used for this analysis was 30 meter by 30 meter cells. Additionally, the SLAMM model will track partial conversion of cells based on elevation and slope.

SUMMARY OF SLAMM INPUT PARAMETERS FOR JOHN HEINZ NWR

Parameter	Global	SubSite 1	SubSite 3
Description		John Heinz	John Heinz 2
NWI Photo Date (YYYY)	1995	1989	1989
DEM Date (YYYY)	1989	2008	2008
Direction Offshore [n,s,e,w]	East	West	West
Historic Trend (mm/yr)	3	2.79	2.79
MTL-NAVD88 (m)	0	-1.387	-1.387
GT Great Diurnal Tide Range (m)	1.65	1.923	1.502
Salt Elev. (m above MTL)	1.45	1.35	1.05
Marsh Erosion (horz. m /yr)	0.3048	0.3048	0.3048
Swamp Erosion (horz. m /yr)	2	2	2
T.Flat Erosion (horz. m /yr)	2	2	2
Reg. Flood Marsh Accr (mm/yr)	4	4	4
Irreg. Flood Marsh Accr (mm/yr)	4	4	4
Tidal Fresh Marsh Accr (mm/yr)	4	4	4
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5
Freq. Overwash (years)	25	25	25
Use Elev Pre-processor [True,False]	TRUE	FALSE	FALSE

Results

John Heinz NWR is predicted to experience some significant effects due to sea-level rise. Refuge tidal fresh marsh – comprising roughly one-third of the refuge – is predicted to be most impacted in SLR scenarios above 0.69 meters. Loss of refuge undeveloped dry land ranges from roughly one quarter to slightly more than one half of its initial acreage.

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Tidal Fresh Marsh	3%	9%	32%	67%	84%
Undeveloped Dry Land	24%	34%	39%	46%	54%
Inland Fresh Marsh	6%	29%	34%	37%	61%
Tidal Swamp	7%	11%	18%	72%	94%
Developed Dry Land	17%	22%	26%	35%	43%
Inland Shore	41%	59%	73%	82%	93%

Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

Refined initial-condition elevations and improved dike and habitat maps have resulted in some differences in model simulations as compared to the previous model run. For example, more tidal-fresh marsh loss is predicted across the range of scenarios run than in the previous set of simulations. Dry-land loss rates range from 24% to 54% as opposed to the previous predicted range of 12-64%. There is less inland fresh marsh acreage in the model due to information about the removal of impoundments at the Henderson and Corps properties; unlike the previous model simulations, the remaining inland fresh marsh is predicted to be vulnerable to sea-level rise, with up to 61% predicted lost.

John Heinz NWR

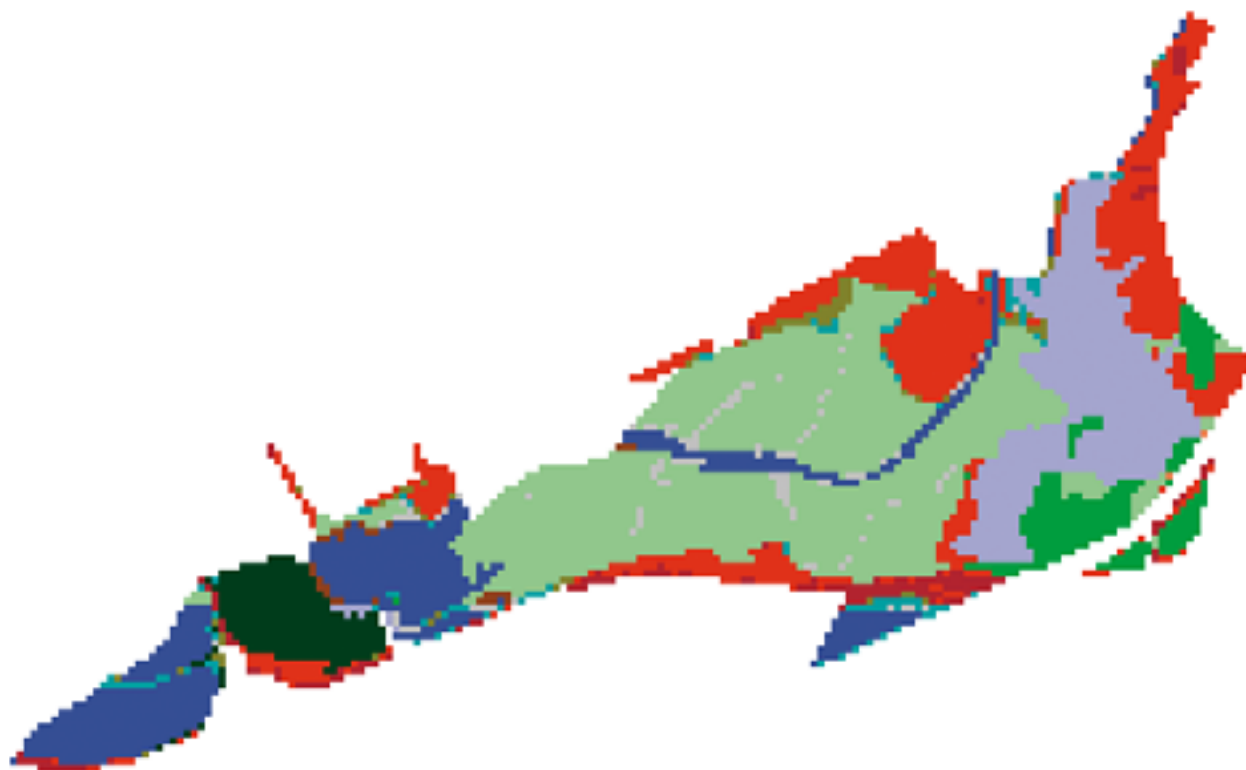**IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100**

Results in Acres

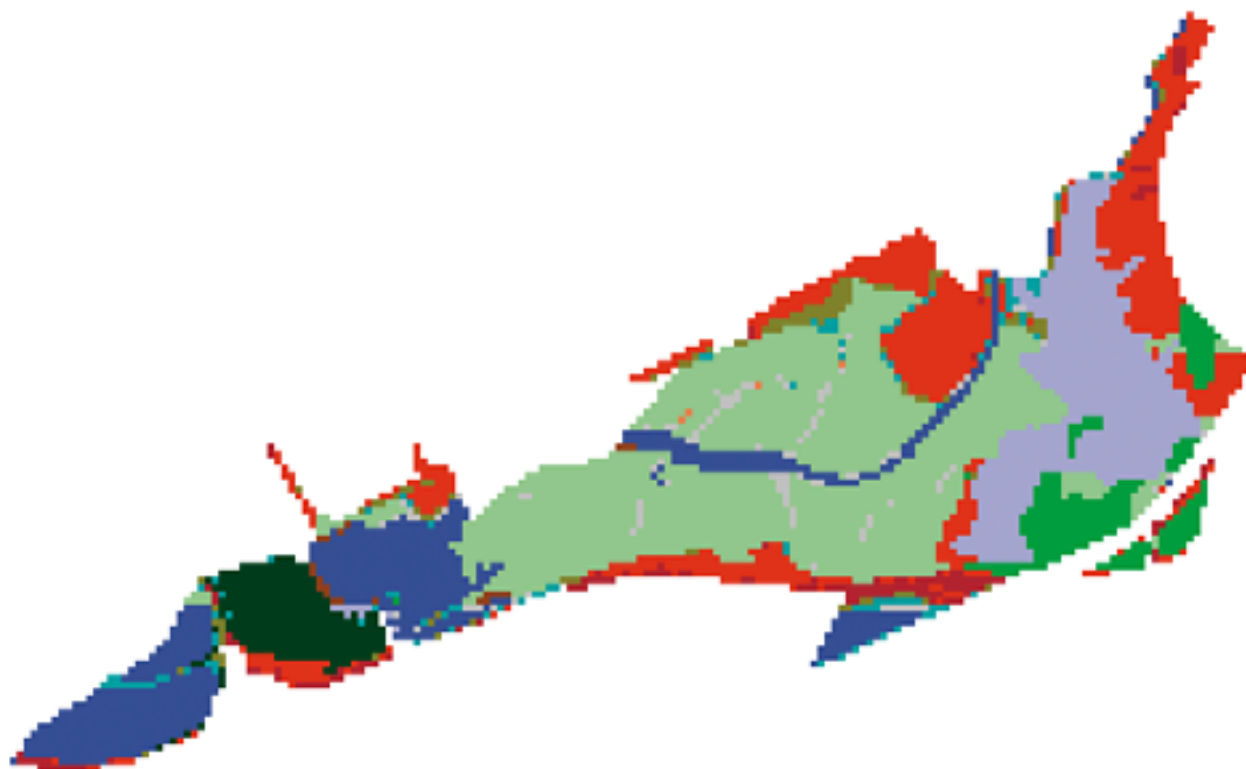|		Initial	2025	2050	2075	2100
	Tidal Fresh Marsh	419.7	410.1	412.2	409.4	406.3
	Undeveloped Dry Land	268.0	219.0	211.9	206.9	202.5
	Inland Open Water	184.6	164.7	164.5	164.3	164.3
	Riverine Tidal	145.0	68.9	68.1	67.2	63.4
	Inland Fresh Marsh	66.5	62.5	62.5	62.5	62.3
	Tidal Swamp	61.6	58.9	58.6	58.0	57.4
	Developed Dry Land	41.6	36.6	36.1	35.3	34.6
	Inland Shore	7.8	7.0	6.3	5.3	4.6
	Estuarine Open Water	0.0	97.1	102.7	108.9	116.4
	Tidal Flat	0.0	0.0	25.4	22.2	21.1
	Regularly Flooded Marsh	0.0	52.3	24.2	25.5	29.8
	Transitional Salt Marsh	0.0	17.4	21.4	25.5	29.3
	Irregularly Flooded Marsh	0.0	0.2	0.9	3.7	2.8
	Total (incl. water)	**1194.7**	**1194.7**	**1194.7**	**1194.7**	**1194.7**

John Heinz NWR, Initial Condition

John Heinz NWR, 2050, Scenario A1B Mean

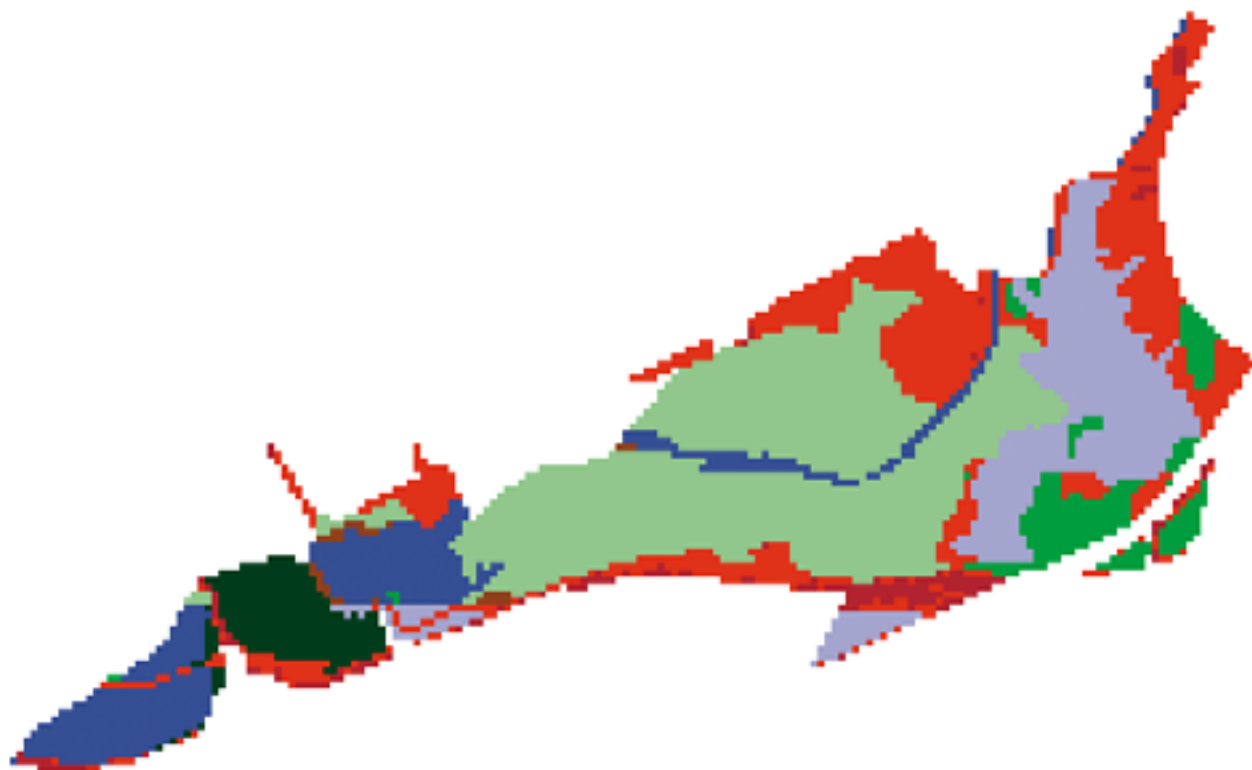John Heinz NWR, 2100, Scenario A1B Mean

John Heinz NWR

IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

|		Initial	2025	2050	2075	2100
	Tidal Fresh Marsh	419.7	406.7	401.2	395.7	381.2
	Undeveloped Dry Land	268.0	217.5	209.8	200.4	176.2
	Inland Open Water	184.6	164.5	164.6	164.4	163.9
	Riverine Tidal	145.0	68.9	67.6	60.7	59.6
	Inland Fresh Marsh	66.5	62.5	62.5	62.3	47.3
	Tidal Swamp	61.6	58.7	58.0	56.6	54.8
	Developed Dry Land	41.6	36.3	35.4	34.2	32.6
	Inland Shore	7.8	6.7	5.5	4.2	3.2
	Estuarine Open Water	0.0	97.6	104.9	123.3	140.2
	Tidal Flat	0.0	0.0	28.6	23.9	20.1
	Regularly Flooded Marsh	0.0	55.2	25.9	33.5	38.1
	Transitional Salt Marsh	0.0	18.1	22.2	26.0	60.0
	Irregularly Flooded Marsh	0.0	1.9	8.6	9.6	17.7
	Total (incl. water)	**1194.7**	**1194.7**	**1194.7**	**1194.7**	**1194.7**

John Heinz NWR, Initial Condition

John Heinz NWR, 2050, Scenario A1B Maximum

John Heinz NWR, 2100, Scenario A1B Maximum
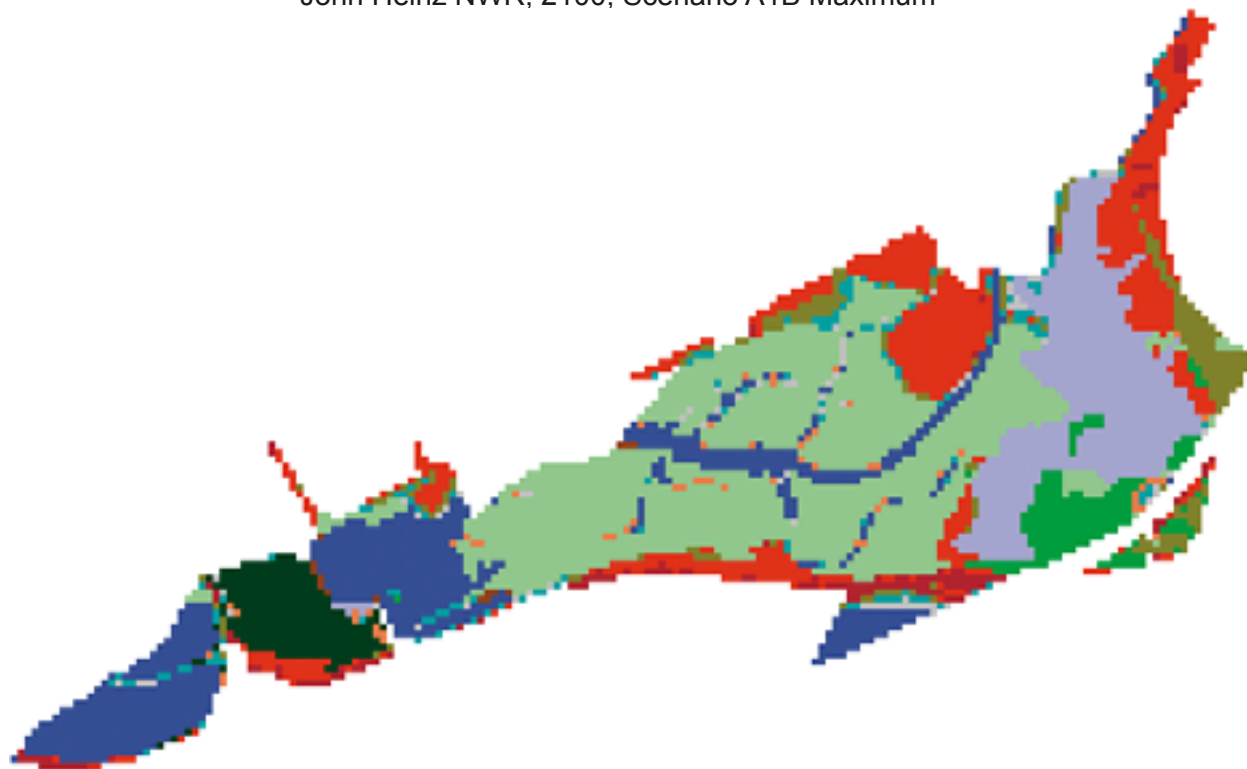
Discussion

In moderate SLR scenarios, only the lowest-elevation areas of the refuge, such as portions of the tidal-fresh marsh bed and water-bordering dry lands, are predicted to be lost to SLR inundation. The pattern of predicted losses within refuge tidal fresh marsh appears to accurately reflect the reality within the refuge as depicted in satellite imagery (Figure I.6).
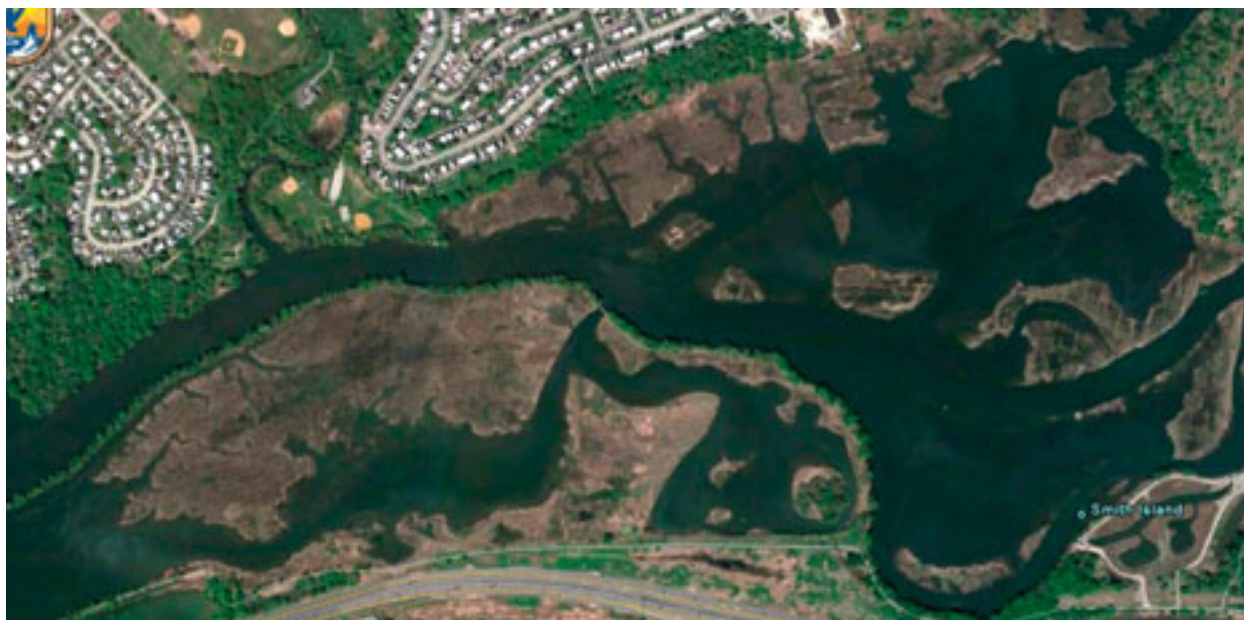
Figure I.6: Satellite image of central portion of John Heinz NWR.

Opening Henderson and the Corps property to tidal influence increases the predicted risk most significantly to the western portion of Henderson. Notably, the Corps property is predicted to be essentially unchanged by sea level rise even though it is now open to tidal influence due to its high initial-condition elevation. The resilience of the Corps property to inundation carries some uncertainty due to a variety of factors including elevation-data vertical accuracy and predicted marsh accretion rates.

The best-available elevation data for this site were based on a two-foot contour map which means that wetland elevations remain somewhat uncertain. Additionally, site-specific accretion data would provide information about local sediment supplies and how effectively marshes will be able to keep up with accelerated sea level rise. Accretion data were derived based on regional averages.

Bibliography

Chen, J. L., Wilson, C. R., and Tapley, B. D. (2006). "Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet." *Science*, 1129007.

Clark, P. U. (2009). *Abrupt Climate Change: Final Report, Synthesis and Assessment Product 3. 4*. DIANE Publishing.

Clough, J. S., Park, R., and Fuller, R. (2010). "SLAMM 6 beta Technical Documentation."

Council for Regulatory Environmental Modeling. (2008). *Draft guidance on the development, evaluation, and application of regulatory environmental models*. Draft, Washington, DC.

Craft, C., Clough, J., Ehman, J., Joye, S., Park, R., Pennings, S., Guo, H., and Machmuller, M. (2009). "Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services." *Frontiers in Ecology and the Environment*, 7(2), 73-78.

Galbraith, H., Jones, R., Park, R., Clough, J., Herrod-Julius, S., Harrington, B., and Page, G. (2002). "Global Climate Change and Sea Level Rise: Potential Losses of Intertidal Habitat for Shorebirds." *Waterbirds*, 25(2), 173.

Glick, P., Clough, J., and Nunley, B. (2007). *Sea-level Rise and Coastal Habitats in the Pacific Northwest An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon*. National Wildlife Federation.

Grinsted, A., Moore, J. C., and Jevrejeva, S. (2009). "Reconstructing sea level from paleo and projected temperatures 200 to 2100 ad." *Climate Dynamics*, 34(4), 461-472.

IPCC. (2001). *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambrdige, United Kingdom, 881.

IPCC. (2007). *Climate change 2007 : the physical science basis*. Cambridge university press, Cambridge.

Kraft, J.C., Yi, H., Khalequzzaman, M., 1992. Geologic and human factors in the decline of the salt marsh lithosome: the Delaware Estuary and Atlantic Coastal zone. Sedimentary Geology 80, 233-246.

Lee, J. K., Park, R. A., and Mausel, P. W. (1992). *Application of geoprocessing and simulation modeling to estimate impacts of sea level rise on the northeast coast of Florida*.

Monaghan, A. J., Bromwich, D. H., Fogt, R. L., Wang, S., Mayewski, P. A., Dixon, D. A., Ekaykin, A., Frezzotti, M., Goodwin, I., Isaksson, E., Kaspari, S. D., Morgan, V. I., Oerter, H., Van Ommen, T. D., Van der Veen, C. J., and Wen, J. (2006). "Insignificant Change in Antarctic Snowfall Since the International Geophysical Year." *Science*, 313(5788), 827-831.

Moorhead, K. K., and Brinson, M. M. (1995). "Response of Wetlands to Rising Sea Level in the Lower Coastal Plain of North Carolina." *Ecological Applications*, 5(1), 261-271.

National Wildlife Federation, and Florida Wildlife Federation. (2006). *An Unfavorable Tide: Global Warming, Coastal Habitats and Sportfishing in Florida*.

Park, R. A., Trehan, M., Mausel, P. W., and Howe, R.C. (1989). "The Effects of Sea Level Rise on U.S. Coastal Wetlands." *The Potential Effects of Global Climate Change on the United States: Appendix B - Sea Level Rise*, U.S. Environmental Protection Agency, Washington, DC, 1-1 to 1-55.

Park, R. A., Lee, J. K., Mausel, P. W., and Howe, R. C. (1991). "Using remote sensing for modeling the impacts of sea level rise.." *World Resources Review*, 3, 184-220.

Park, R. A., Lee, J. K., and Canning, D. J. (1993). "Potential Effects of Sea-Level Rise on Puget Sound Wetlands." *Geocarto International*, 8(4), 99.

Pfeffer, W. T., Harper, J. T., and O'Neel, S. (2008). "Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise." *Science*, 321(5894), 1340-1343.

Rahmstorf, S. (2007). "A Semi-Empirical Approach to Projecting Future Sea-Level Rise." *Science*, 315(5810), 368-370.

Titus, J. G., Park, R. A., Leatherman, S. P., Weggel, J. R., Greene, M. S., Mausel, P. W., Brown, S., Gaunt, C., Trehan, M., and Yohe, G. (1991). "Greenhouse effect and sea level rise: the cost of holding back the sea." *Coastal Management*, 19(2), 171–204.

Titus, J. G., and Strange, E. (Eds.). (2008). "Background Documents Supporting Climate Change Science Program synthesis and Assessment Product 4.1 Coastal Elevations and Sensitivity to Sea-Level Rise.." *EPA 430R07004, http://www.epa.gov/climatechange/effects/coastal/background.html.*

Vermeer, M., and Rahmstorf, S. (2009). "Global sea level linked to global temperature." *Proceedings of the National Academy of Sciences*, 106(51), 21527.